426

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 426

THE EFFECT OF HUMIDITY ON ENGINE POWER AT ALTITUDE

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By D. B. BROOKS and E. A. GARLOCK

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/h	k. p. h.	mi./hr.	m. p. h.
		m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s^2 $= 32.1740$ ft./sec.^{2}

m, Mass $= \frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 760 mm $= 0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m^3 $= 0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\frac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $= \frac{1}{2}\rho V^2$.

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force.

i_w, Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting (relative to thrust line).

Q, Resultant moment.

Ω, Resultant angular velocity.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/s, the corresponding number is 274,000.

C_p, Center of pressure coefficient (ratio of distance of $c. p.$ from leading edge to chord length).

α, Angle of attack.

[illegible], Angle of downwash.

α_o, Angle of attack, infinite aspect ratio.

α_i, Angle of attack, induced.

α_a, Angle of attack, absolute.

(Measured from zero lift position.)

γ Flight path angle.

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By D. B. BROOKS and E. A. GARLOCK
Bureau of Standards

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

From tests made in the altitude chamber of the Bureau of Standards, it was found that the effect of humidity on engine power is the same at altitudes up to 25,000 feet as at sea level. Earlier tests on automotive engines, made under sea-level conditions, showed that water vapor acts as an inert diluent, reducing engine power in proportion to the amount of vapor present.

By combining the effects of atmospheric pressure, temperature, and humidity, it is shown that the indicated power obtainable from an engine is proportional to its mass rate of consumption of oxygen. This has led the National Advisory Committee for Aeronautics to adopt a standard basis for the correction of engine performance, in which the effect of humidity is included.

INTRODUCTION

This report[1] covers work done at the Bureau of Standards as part of an investigation of the effect of humidity on engine performance, undertaken in 1929 at the request of the Bureau of Aeronautics, Navy Department. Tests made on a 6-cylinder automobile engine at sea level (references 1 and 2) indicated that loss of engine power caused by humidity varied directly with pressure of water vapor. Later tests on a 4-cylinder truck engine (reference 3), and unpublished tests on the latter and on a single-cylinder variable compression C. F. R. engine substantiated the results of the above tests. In all cases engine-indicated power was found to be proportional to dry air pressure over the narrow range available.

To verify this latter observation, tests have been made in the altitude chamber on a 12-cylinder Curtiss *D-12* engine at pressures corresponding to altitudes from sea level to 25,000 feet. At each "altitude" humidity was varied from the maximum likely to occur to the minimum attainable. To minimize experimental error, all runs of the series were made at a constant air temperature of 30° C.

The results of these additional tests show that engine-indicated power varies linearly with dry air pressure. This necessitates modifying the correction formula as follows:

In correcting engine-performance data to standard conditions, indicated power and rate of fuel flow are multiplied by the correction factor F,

$$F=\frac{P_s}{B_o-H_o}\sqrt{\frac{T_o+273}{T_s+273}}$$

where B_o—observed total pressure (barometer), mm Hg;
H_o—observed pressure of water vapor (humidity), mm Hg;
T_o—observed air temperature, °C.;

and P_s and T_s are standard dry air pressure[2] and temperature—the values of these quantities being given below:

Altitude (feet)	P_s	T_s
Sea level.	750.0 mm Hg	+15.0 °C.
5,000	627.7	+5.1
10,000	520.4	−4.8
15,000	427.8	−14.7
20,000	348.6	−24.6
25,000	281.7	−34.5
30,000	225.5	−44.4

Test apparatus.—As the general design and method of operation of the Bureau of Standards altitude laboratory have been described (references 4 and 6), mention will be made here only of modifications required by these tests.

In the altitude laboratory, moisture is removed from the carburetor air supply by cooling this air to about −40° C., before reheating it electrically to the desired temperature. To increase the efficiency of snow removal from the cooled air, additional baffles were installed in the settling chamber. These resulted in obtaining humidities as low as 0.3 to 0.5 mm mercury in the carburetor air supply when water vapor pressure in the external air was 5 to 15 mm mercury.

Provision was made for injection of dry steam into the carburetor air supply, injection occurring subsequent to the passage of the air through the heating grids and the altitude control valve.

A sampling tube, inserted either in the header above the air horn or ahead of the air metering Venturi, was

[1] The problem was outlined and the experimental results were analyzed by the senior author. The horsepower versus mixture ratio data presented in Figure 2 are the result of measurements and computations by the altitude laboratory staff under the direction of the junior author. The psychrometric measurements were made by Messrs. H. H. Allen and N. R. White.

[2] Adopted by the N. A. C. A. on October 22, 1931. The dry air pressures, P_s, are derived from the N. A. C. A. standard atmosphere by assuming that the mean humidity at sea level is 10 mm Hg, and that it varies with altitude approximately as indicated by Dr. J. Hann (Lehrbuch der Meteorologie).

used to withdraw air continuously. In the former case, proper correction was made to the measured value of total air flow for the quantity thus diverted from the engine, which was passed through a modified psychrometer for the purpose of humidity control, and was then rejected to the exhaust pump. Samples were also analyzed chemically in a modified Wolpert apparatus to verify the psychrometric formula used.[3]

Test conditions and procedure.—From a study of available meteorological data, it was decided that 100 per cent relative humidity might occur at the highest temperature recorded for each altitude. Runs therefore were made at each altitude with this maximum and with the minimum attainable humidity. The variation of probable maximum humidity with altitude is indicated in Figure 1. On the same plot the ranges of humidity used in these tests are shown.

In order to minimize the effects of factors other than humidity, all test conditions except air pressure were

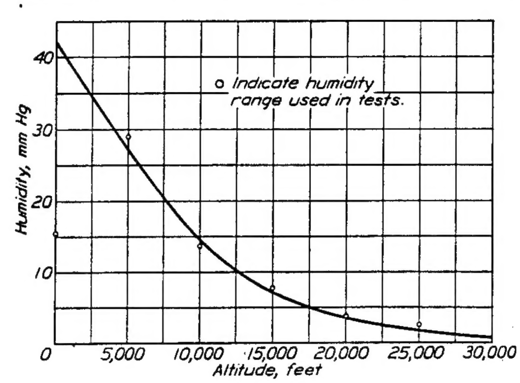

FIGURE 1.—Variation of maximum humidity with altitude

maintained at their respective sea-level values throughout the series of tests. The temperatures maintained were as follows:

	°C.
Jacket water outlet	77
Crankcase oil inlet	60
Carburetor air supply	30

In all tests the fuel used was a blend of domestic aviation gasoline and motor benzol having a knock rating of approximately 82 octane number.

Chamber and exhaust manifold pressures were maintained closely equal to air-horn pressure; corrections were applied to the observed power values for any departures from equality.

For each test, the Curtiss *D-12* engine was warmed up and was run at sea-level conditions until the inducted air reached −40° C. in the cooling chamber. During this period the engine power was observed to ascertain whether the engine was in proper condition throughout.

[3] A similar psychrometer was subsequently studied at altitudes up to 30,000 feet. No departure from the standard psychrometric formula was observed. Results will be published later.

When these conditions were attained, pressures were brought to the desired values, and air-horn air temperature was stabilized at 30° C. Complete measurements were then taken at seven air-fuel ratios, three giving practically maximum power and two each definitely richer and leaner than that for maximum power. (See fig. 2.) During each run, psychrometer readings were made, and during one run an air sample was drawn for chemical determination of humidity.

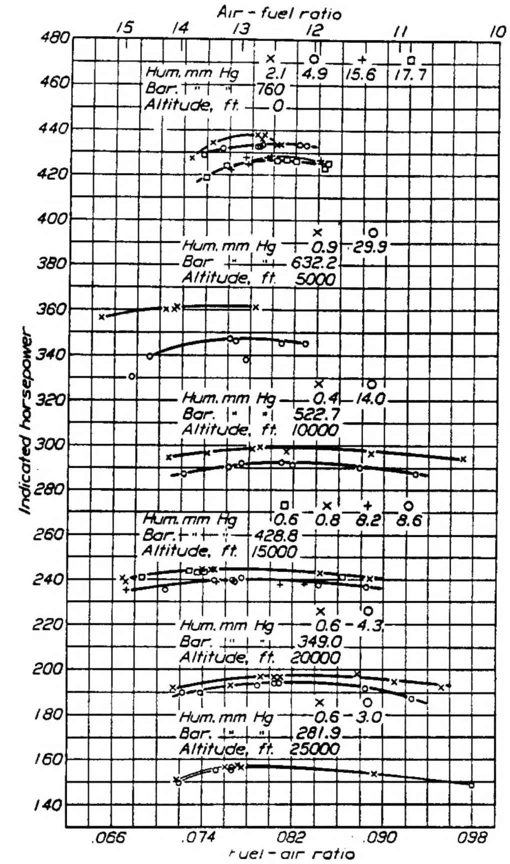

FIGURE 2.—Altitude chamber tests

At the conclusion of this first set of runs, dry steam was injected into the air-horn air stream at a rate such as to maintain the desired higher value of humidity. When conditions had been stabilized, another set of runs was made in the manner described above.

Subsequently, sufficient motoring runs were made to enable determination of the engine friction under all test conditions.

TEST RESULTS

The test results are plotted as indicated horsepower versus air-fuel ratio in Figure 2. On the figure are listed the symbol, humidity barometric pressure, and equivalent altitude for each test.

From Figure 2 the maximum power obtained during each test was estimated from the appropriate curve. The resulting values are plotted against dry air pressure in Figure 3. A summary of the series of runs is shown in Figure 4 in which the power loss, expressed in per cent of the total power, is plotted against humidity in per cent of total pressure. Sea-level tests on a C. F. R. (1-cylinder) test engine are plotted in Figure 5.

Table I lists for each run the altitude, total pressure, humidity, dry air pressure, maximum indicated power, dry air fuel ratio for maximum power, the maximum indicated horsepower computed from (A) dry air pressure and (B) humidity, as hereinafter explained, and the residuals, or differences between the observed and computed values of maximum power. Table II lists the results plotted in Figure 4.

DISCUSSION OF TEST RESULTS

Figure 5, presenting results of a sea-level test on the 1-cylinder C. F. R. engine, is of interest in that it

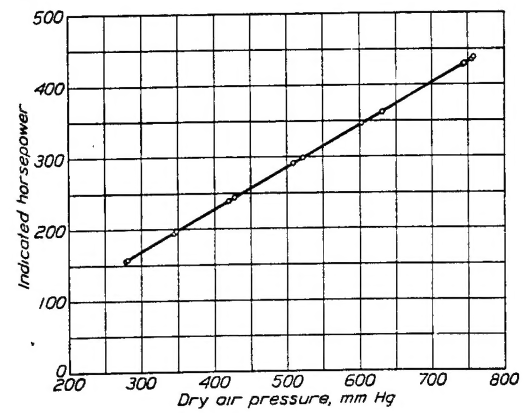

FIGURE 3.—Variation of indicated power with dry-air pressure

demonstrates that the variation of power with pressure of water vapor is linear within the precision of observations. This is substantiated by the very close negative correlation of power with pressure of water vapor.[4]

Figure 3, summarizing all altitude tests, is the first instance in which the indicated power of an engine at altitude has been demonstrated to be linearly related to dry air pressure. The agreement of the observed power with the straight line is quite good, as shown in the figure, and by the seventh, ninth, and tenth columns of Table I. The greatest deviation of any of the 14 observed values from the line is 1.5 horsepower. A further demonstration of the close relationship of these observed power values to dry air pressure is their extremely high correlation.

However, if the straight line fitting the points be extrapolated to zero pressure, the power value obtained is −6.75 horsepower. In view of the closeness of the correlation of power with dry air pressure, this suggests that the motoring method of measuring friction may

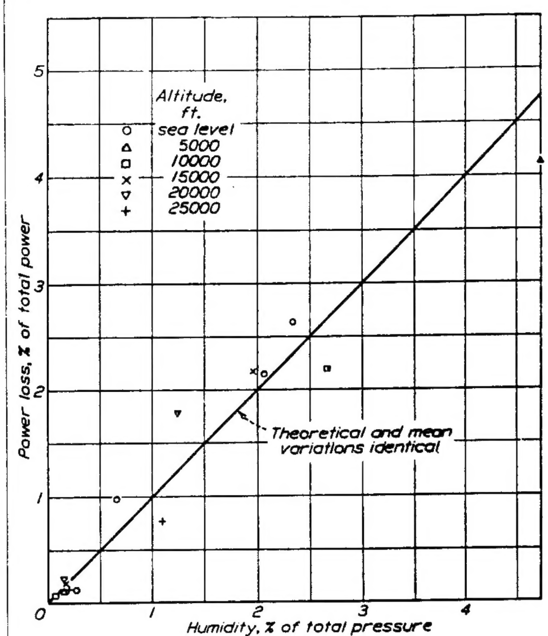

FIGURE 4.—Effect of humidity on power

lead to a slightly erroneous result, and that true indicated power, defined as the integral of gas pressure on

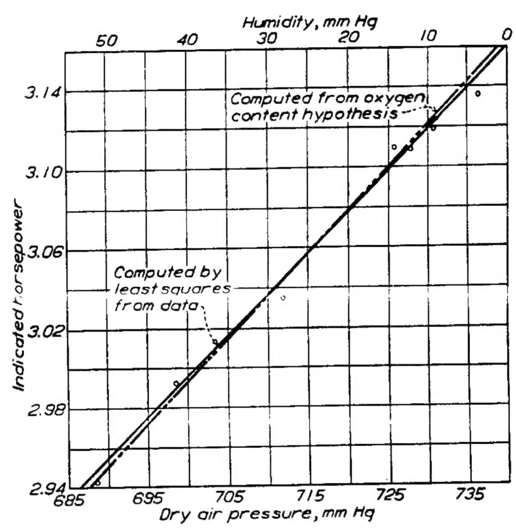

FIGURE 5.—Effect of humidity on power

the piston throughout the cycle, varies in exact accord with dry air pressure over the range studied.

In Figure 4, and in Table II the results of the altitude tests are presented in such form as to show that

[4] See Note 1, Appendix, for this and subsequent correlation coefficients.

when the power loss is expressed in per cent of the total power, and the humidity in per cent of the total pressure, their values are equal. Because of the somewhat unequal weighting of the data inherent in this form of comparison, exact equality is shown. (Fig. 4 and bottom line of Table II.) By a different treatment, whereby each observation is given equal weight, the variation of indicated power is found to be 100.4 per cent of the variation of humidity, when both are expressed in per cent, as stated above.

In Table I, the seventh column is computed from the linear equation deduced by least squares analysis of the results plotted in Figure 3. This equation is

$$P=0.58554B-6.75$$

where P = indicated horsepower,
B = dry air pressure, mm mercury.

To compute the values listed in the eighth column of Table I, the line fitting the observed power values at each altitude was extrapolated to zero humidity, giving the value of power which would have been obtained by operating with dry air at that altitude. From this value indicated power at the observed humidities was computed by assuming power loss to vary with humidity (see B, Table I), as demonstrated in Table II.

Columns 9 and 11 of Table I give the differences between observed and computed values of the power. In column 10 the differences given in column 9 are expressed in per cent of sea-level power; column 12 similarly lists the differences given in column 11 expressed in per cent of power at the dry air pressure corresponding to the altitude. At the bottoms of columns 9–12 the average and maximum deviations and probable errors are listed. It is apparent from these residuals that the indicated power is correlated about as well with dry air pressure as with humidity.

In an attempt to determine whether the effect of humidity would differ materially at the low temperatures corresponding to high altitude conditions, several runs were made, at 25,000 feet, with air-horn air temperatures between −20° C. and −10° C., the intention being to operate first dry and later with air saturated at these temperatures. The dry runs were readily obtained, but in many cases a large drop in power, accompanied by irregular operation and often failure of the engine, quickly followed any increase in humidity. This was traced to ice formation in the carburetor. In one test, however, it was possible to get a "flash" reading of the power loss caused directly by increase of humidity. For an increase of humidity of ¾ per cent expressed in terms of total pressure, the power loss was roughly 1 per cent, the power remaining constant for two or three minutes before irregular operation and a further sharp loss of power occurred. It was concluded that the effect of humidity on power is not appreciably affected by temperature, when operating at high altitudes.

The fact that the magnitude of the effect of humidity is dependent on the vapor pressure rather than on the relative humidity is well illustrated by a series of tests on a class B engine. These tests were run under conditions of air temperature, pressure, and humidity selected at random within the available ranges. This was done to eliminate the necessity of applying corrections for deviations from selected values.

Power readings were taken at each of six to eight values of spark advance for each of five values of fuel consumption at each atmospheric condition. As observations were made under 43 sets of atmospheric conditions, this test series comprised a total of about 1,500 power readings.

The observed values of power at a given rate of fuel consumption were plotted against spark advance; the peak values of these curves for a given atmospheric condition were then plotted against fuel consumption. The peak of the resulting curve was considered to represent the maximum power value for the given atmospheric condition. These power values were then converted to indicated torque by adding motoring friction.

In developing results from these data a method was used which involved a minimum of assumption. It was assumed that the power was affected by total pressure and pressure of water vapor, and is an exponential function of the air temperature, the equation used being

$$P=a(B+bH)T^c \tag{1}$$

Where P = indicated power
B = total air pressure } Same units.
H = pressure of water vapor }
T = absolute temperature

and a, b, c, are constants whose values are to be found. A solution by the method of least squares gave $b=-1.014$. To fit the oxygen content hypothesis, the value of b should be -1; the agreement is consequently very good, particularly in view of the quite general nature of (1).

A much better means of deciding whether the agreement of the results with the oxygen content hypothesis is markedly superior to their agreement with the hypothesis that power is affected by relative humidity (reference 5) is afforded by evaluation of the respective correlation coefficients.

This was done, using the data given in Table III. The correlation of power with relative humidity was such as would be obtained once in three times from uncorrelated material; hence there is no reason to believe, from these data, that power is related to relative humidity. However, the correlation coefficient of power with vapor pressure of water, found from the same data is of such magnitude as would not occur in 10^{15} times by chance from uncorrelated material. This amounts to complete confirmation of the oxygen

content hypothesis, together with rejection of the relative humidity hypothesis cited above.

Since engine power depends on air temperature as well as on humidity, effects caused by the former tend to obscure results of variations of the latter. However, if the effects of temperature were wholly eliminated, correlations with relative and with absolute humidity would be equal, as, at constant temperature, relative humidity and pressure of water vapor are two measures of the same quantity. Partial correlation, which tends to eliminate temperature, consequently indicates a very close connection between power and either relative humidity or pressure of water vapor.

It is concluded that the effect of humidity on engine power is not dependent on relative humidity, and hence is independent of temperature. All available data confirm this conclusion.

A study of the data in Table I indicated no apparent variation of air-fuel ratio for maximum power with altitude. Correlation of the air-fuel ratios with altitude in feet, total pressure, and dry-air pressure indicates that there is no variation in air-fuel ratio for maximum power with altitude over the range studied.

Correlation of air-fuel ratio with humidity did not indicate any significant connection between these factors. However, the lower value [5] obtained for dry-air-fuel ratio is in agreement with the data presented in N. A. C. A. Technical Note No. 309, showing the desirability of plotting power against dry-air-fuel ratio for comparison purposes.

A study of the class B engine data further reveals a dependence of optimum spark advance for maximum power on humidity, this dependence resulting in an increase of optimum advance with increasing humidity, as was found in the work reported in N. A. C. A. Technical Note No. 309. (Reference 1.) The rate of change of advance found was only 0.7° per centimeter mercury increase in pressure of water vapor, as compared with the value 2.1 found from the earlier work. However, the earlier value is more likely to be the better, as it was obtained under controlled conditions, while the later value was deduced from the tests made under random conditions. No evidence was found for change of spark advance with air temperature.

[5] See Note 1, Appendix

CONCLUSIONS

This research leads to conclusions as follows:

1. The action of humidity on engine performance is not affected by change of air pressure (altitude) or air temperature.
2. The effect of humidity is to decrease engine indicated power in proportion to the concomitant decrease of dry-air pressure.
3. The maximum obtainable indicated power of an engine under *any* conditions is directly proportional to its mass rate of consumption of oxygen under these conditions.
4. The findings reported in N. A. C. A. Technical Note No. 309 have been substantiated over more extended ranges of temperature and humidity and over a wide range of air pressure.
5. Over the range covered by these tests the dry-air-fuel ratio for maximum power is invariant with altitude.

APPENDIX

CORRELATION COEFFICIENTS

NOTE 1

The use of correlation herein follows that of R. A. Fisher, "Statistical Methods for Research Workers," in which the correlation coefficient r, is

$$r=\frac{\Sigma\, x\, y}{\sqrt{\Sigma x^2\ \Sigma y^2}} \tag{1}$$

and its probable error is found by transforming the correlation to

$$z=\frac{\log_e\ (1+r)-\log_e\ (1-r)}{2} \tag{2}$$

evaluating the probable error of z,

$$\sigma_z=\frac{1}{\sqrt{n-3}} \tag{3}$$

and transforming back to the units of (1). This treatment minimizes the effects of skew distribution and of small samples.

The coefficients found for the correlations referred to herein are as follows:

Engine	Correlation of—	With—	Coefficient and error		Random probability
C. F. R.	Indicated power	Pressure of water vapor	−0.996	−0.003 +.009	Practically zero.
D-12	do	Dry-air pressure	+.99996	±.0002	Do.
Class B	do	Relative humidity	−.17	±.16	0.3
		Pressure of water vapor	.885	±.035	Less than 10^{-18}.
Class B	do.[1]	Relative humidity	−.89	±.03	Do.
		Pressure of water vapor	−.96	±.01	Practically zero.
D-12	Dry air fuel ratio for maximum power	Altitude (feet)	−.02	±.28	.95
		Total pressure	+.01	±.28	.97
		Dry-air pressure	+.02	±.28	.95
D-12	do	Pressure of water vapor	−.09	±.28	.75
D-12	Total air fuel ration for maximum power	do	+.22	±.27	.5
Class B	Spark advance for maximum power	do	+.43	±.16	.005
		Temperature	+.09	±.16	.6

[1] Partial correlations.

The last column lists the probability of obtaining from uncorrelated material a coefficient as large as that given in the fourth column.

ICE FORMATION

NOTE 2

Had the irregular operation and engine failure due to ice formation mentioned in this report occurred only with near-freezing temperatures, these difficulties might be considered peculiar to the altitude chamber. However, in preliminary runs to determine the minimum temperature for satisfactory operation, failure from this source occurred with air-horn air temperatures as high as +20° C., when the humidity was increased nearly to saturation.

This may occur also in flight. Thus, if the air humidity is near saturation, condensation will occur when operating at full throttle unless the air at the carburetor Venturi has been heated about 20° C. above outside air temperature. If the outside air temperature is but little above freezing, ice formation will result. The possibility of ice forming increases with increasing volatility of fuel. The preventative is to insure enough heat transfer to the carburetor to counteract the cooling consequent upon vaporization of the fuel.

Bureau of Standards,
Washington, D. C., *February 24, 1932.*

TABLE I

Altitude (feet)	Total pressure (mm Hg)	Humidity (mm Hg)	Dry air pressure (mm Hg)	Maximum (i. hp)	Air fuel ratio for max. i. hp	i. hp computed from— Dry air pressure A	Humidity B	Residuals From A hp	%	From B hp	%
1	2	3	4	5	6	7	8	9	10	11	12
Sea level.	760.0	2.1	757.9	438.2	12.8	437.0	436.8	1.2	0.27	1.4	0.32
Sea level.	760.0	4.9	755.1	434.4	12.4	435.4	435.1	1.0	.22	.7	.16
Sea level.	760.0	15.6	744.4	428.8	12.4	429.1	428.9	.3	.08	.1	.02
Sea level.	760.0	17.7	742.3	427.0	12.5	427.9	427.6	.9	.21	.6	.15
5,000	632.2	2.9	631.3	361.8	13.3	362.9	363.0	1.1	.25	1.2	.35
5,000	632.2	29.9	602.3	347.3	12.9	345.9	346.1	1.4	.32	1.2	.35
10,000	522.7	.4	522.3	299.0	12.4	299.1	299.8	.1	.02	.8	.26
10,000	522.7	14.0	508.7	292.6	12.3	291.1	291.8	1.5	.33	.8	.26
15,000	428.8	.6	428.2	244.6	13.0	244.0	244.5	.6	.14	.1	.05
15,000	428.8	.9	427.9			243.8	244.3	.8	.18	.3	.11
15,000	428.8	8.2	420.6	239.7	12.6	239.5	240.0	.2	.04	.3	.13
15,000	428.8	8.6	420.2			239.3	239.8	.4	.09	.1	.04
20,000	349.0	.6	348.4	197.2	12.2	197.3	196.8	.1	.02	.4	.23
20,000	349.0	4.3	344.7	194.1	12.2	195.1	194.5	1.0	.22	.4	.23
25,000	281.9	.5	281.4	157.4	12.8	158.0	157.6	.6	.14	.2	.15
25,000	281.9	3.0	278.9	156.4	12.8	156.5	156.2	.1	.03	.2	.15
						Average deviation		.70	.16	.57	.18
						Maximum deviation		1.5	.33	1.4	.35
						Probable error		.58	.13	.49	.15

TABLE II

Altitude	Humidity (% of total pressure)	Power loss (% of total power)
0	0.27	0.12
0	.65	.99
0	2.05	2.16
0	2.33	2.65
5,000	.15	.12
5,000	4.74	4.13
10,000	.07	.06
10,000	2.67	2.20
15,000	.17	.18
15,000	1.96	2.19
20,000	.16	.23
20,000	1.24	1.80
25,000	.19	.13
25,000	1.08	.77
Mean	1.266	1.266

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TABLE III

CLASS B TEST DATA

(Corrected to 760 mm Hg total pressure)

Run No.	Air temperature °K	Humidity %	Humidity mm Hg	Indicated torque
1	325.7	33.3	35.3	161.25
2	311.3	36.2	18.3	169.0
3	323.7	17.7	17.0	166.5
4	302.8	67.9	21.4	169.75
5	304.7	67.8	23.8	169.2
6	306.1	67.6	25.7	168.5
7	307.1	77.4	[illegible]	165.9
8	313.6	40.7	23.3	167.5
9	302.1	65.1	19.7	170.5
10	304.5	56.4	19.6	170.5
11	304.6	43.8	15.3	171.6
12	314.4	25.0	14.9	168.75
13	323.6	14.8	14.1	167.3
14	317.5	38.2	26.8	166.7
15	305.7	50.4	18.7	170.0
16	298.6	35.7	8.8	173.9
17	313.6	24.0	13.7	168.1
18	290.6	53.2	13.9	170.7
19	301.0	73.6	20.9	169.0
20	298.4	48.5	11.8	171.8
21	314.2	27.4	16.2	168.3
22	313.9	49.7	28.9	167.0
23	312.2	16.2	8.6	168.8
24	313.5	26.5	15.1	168.4
25	314.3	47.2	28.0	164.5
26	311.7	65.6	39.8	162.0
27	313.0	53.1	51.6	160.35
28	323.6	13.2	12.6	168.0
29	323.2	55.4	51.8	158.4
30	316.5	51.5	34.3	163.8
31	298.5	52.7	12.9	171.2
32	300.0	57.5	15.4	171.0
33	302.2	65.1	19.8	169.1
34	303.3	76.2	24.7	167.6
35	303.7	86.0	28.5	167.8
36	313.3	22.4	12.6	168.2
37	324.0	11.6	11.3	167.0
38	323.2	24.3	22.7	164.9
39	322.3	40.0	35.8	161.7
40	323.1	46.7	43.5	160.8
41	301.9	22.5	6.7	173.8
42	307.1	20.2	8.1	172.5
43	308.4	30.1	13.0	170.5

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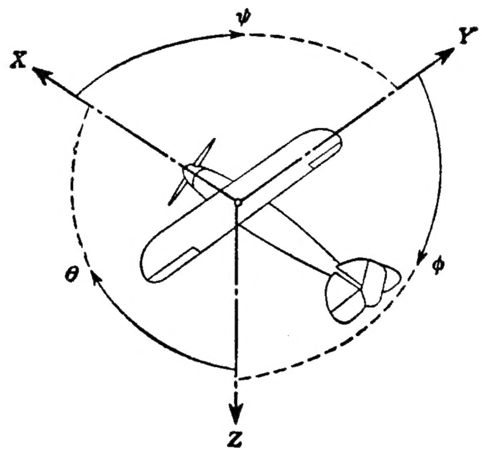

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	ϕ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{qbS} \qquad C_m = \frac{M}{qcS} \qquad C_n = \frac{N}{qbS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.

p, Geometric pitch.

p/D, Pitch ratio.

V', Inflow velocity.

V_s, Slipstream velocity.

T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$.

C_S, Speed power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$.

η, Efficiency.

n, Revolutions per second, r. p. s.

Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.

1 kg/m/s = 0.01315 hp

1 mi./hr. = 0.44704 m/s

1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.

1 kg = 2.2046224 lb.

1 mi. = 1609.35 m = 5280 ft.

1 m = 3.2808333 ft.